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Some Problems in the Theory of the Formation of Clouds and Precipitation

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Abstract

Research on clouds and precipitation has undergone considerable development in the Soviet Union during the last forty years. In the pre-war years, a great deal of data was collected from the network of weather stations on clouds and precipitation; synoptic methods of forecasting these phenomena were developed; a substantial amount of laboratory research was carried out on thunderstorm electricity and the mechanism of precipitation formation; and research was begun on clouds in the vicinity of mountains. Immediately after the war, research was renewed in the Soviet Union on the active modification of clouds and fog. Physical methods have been developed for forecasting cloudiness and precipitation, based on the solution to dynamic atmosphere equations and energy relationships. In recent years, more and more effort has been put into cloud research and into the development of methods of active modification.

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I. INTRODUCTION

In the 40 years since the appearance of V.I. Lenin's decree on "The Organization of a Meteorological Service in the RSFSR," research on clouds and precipitation has undergone considerable development in the Soviet Union.

This research was originally begun at the Main Geophysical Observatory (GGO), the Central Institute of Forecasting (T͡sIP), the Central Aerological Observatory (T͡sAO), the State Hydrological Institute (GGI), and at several institutes of the Academy of Sciences, namely, the Institute of Theoretical Geophysics, the Elbrus expedition, and the Institute of Physical Chemistry.

In 1931, the Institute of Precipitation was founded in Moscow, with branches in Leningrad, Odessa, and Ashkhabad. This was the first institute exclusively devoted to the solution of problems involved in the artificial production of precipitation. In 1934, the Leningrad branch was reorganized into the Institute of Experimental Meteorology with V. N. Obolenskii as the director. However, at that time, the state of knowledge about precipitation and the technical possibilities for weather modification were not such as to hold any promise for solution of the problem of the artificial production of precipitation or other problems of cloud modification.

In the pre-war years, a great deal of data was collected from the network of weather stations on clouds and precipitation: synoptic methods of forecasting these

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phenomena were developed: a substantial amount of laboratory research was carried out on thunderstorm electricity and the mechanism of precipitation formation: and research was begun on clouds in the vicinity of mountains, along with theoretical studies on the processes of condensation and coagulation.

The greatest advances in the physics of clouds and precipitation occurred after World War II. The use of aviation and radar and the development of a radiosonde network (initiated by P. A. Molchanov) permitted a large amount of observational data on clouds and precipitation to be collected under natural conditions. This served as the basis for the creation of the theory of precipitation. Immediately after the war, research was renewed in the Soviet Union on the active modification of clouds and fog.

Research on cloud structure was conducted at the GGO, T͡sAO, Moscow and Leningrad Universities, and the Institute of Applied Geophysics of the Academy of Sciences of the USSR (IPG).

Laboratory research on the mechanism of precipitation formation was developed at the Institute of Physical Chemistry, the IPG of the Academy of Sciences of the USSR (AN SSSR), the Institute of Crystallography, the GGO, the T͡sAO, Leningrad State University (LGU), and the Leningrad Hydrometeorological Institute (LGMI). Radar studies of clouds were carried out at the T͡sAO and the GGO.

After the war, Soviet meteorology was among the world's leaders both in the area of field and laboratory research on precipitation formation and in the development of a theory of precipitation, and it played a prominent role in a number of directions. It was in the Soviet Union that detailed studies were made on the microstructure of clouds (Zait͡sev, Selezneva, Borovikov, Gaivoronskii, Minervin, Chuvaev, Khimach, Nikandrova, and others). The Deri͡agin School at the Institute of Physical Chemistry, Nikandrov and Krasikov at the GGO, and others conducted numerous studies of the mechanism of condensation and coagulation of cloud particles. In the Soviet Union, the basis for a quantitative theory of rain was laid from droplet-structure clouds and a theory of h' .. Physical methods based on the solution to dynamic atmosphere equations and energy relationships, have been developed for forecasting cloudiness and precipitation.

In recent years, more and more effort has been put into cloud research and into the development of methods of active modification. Wide-ranging research has been conducted in the Ukraine (Ukrainian Hydrometeorological Research Institute (UkrNIGMI), Institutes of the Academy of Sciences of the Ukrainian SSR (AN USSR), and Kiev and Odessa Universities) and in Georgia (the Geophysics Institute of the Academy of Sciences of the Georgian SSR (AN GruzSSR) and the Transcaucasian Hydrometeorological Research Institute [ZakNIGMI]).

Cloud researchers are no longer counted by ones or tens; hundreds of people now participate in this research. This can be seen from conference participation on the physics of clouds and precipitation in recent years.

2. SOME PROBLEMS IN THE THEORY OF PRECIPITATION

Let us dwell in more detail on certain problems in the theory of clouds and precipitation recently developed at the GGO. As before, attention at the GGO has been focused primarily on the study of convective clouds.

As previously mentioned, laboratory and theoretical studies of the various processes involved in precipitation formation had already begun in the pre-war years. Direct work on the creation of a quantitative theory of precipitation was begun in 1945-1946. The first step was to compute the growth, of an individual droplet, due to condensation and coagulation in a cloud of uniform structure and in the presence of a constant ascending current. In 1948, droplet growth was computed with allowance for the change in the size of cloud droplets during the process of cloud growth (Shishkin, 1948). The calculations were restricted to the initial stage of precipitation fall from droplet structure clouds. Until then, no detailed information had been obtained on the form of the size distribution of droplets. The only clear result was that the distribution curve was characterized by the presence of a single maximum. Köhler's earlier assertion that there are a number of maxima was the result of incomplete statistics. This was shown conclusively in 1950 by P. V. D'iachenko (1959). The Smoluchowski formula for the size distribution of the droplets was used in the computations, although, strictly speaking, that formula is applicable only to condensation nuclei. The Smoluchowski distribution was determined by collisions of particles in Brownian motion.

In 1952, work was begun on the development of a quantitative theory of hail (Shishkin, 1952).

In 1955, the author showed that the Khrgian and Mazin distribution (Khrgian, 1952), namely

$$n(r) = ar^2 e^{-br}$$

and the Smoluchowski distribution, that is,

$$n(r) = Ar^2 e^{-Br^2}$$

lead to approximately the same result for precipitation both for the time of precipitation and for the rain droplet size (Shishkin, 1955).

In 1960, the computations encompassed the entire period of precipitation (rain from pure water clouds and hail) with allowance for the washing out of clouds by precipitation (Barukova, 1960). In this case, it was possible to obtain data on:

(1) the change in the size of the prec. itation particles during the process of rainfall r hail, (2) c. nges in the intensity of rain or hail with time, and (3) the total amount of fallen precipitation. The problem encompasses the entire period of precipitation from the clouds, which grow vigorously at a constant rate in the initial period of development (up to the beginning of precipitation), after which the ascending currents in the clouds cease. The computations for clouds with a constant ascending current are carried out up to the instant that maximum precipitation intensity is achieved.

The extremely time-consuming precipitation calculations were performed by I. I. Kamaldina, T. S. Uchevatkina, I͡u. A. Barukova, and N. S. Shishkin.

Up to the present time, the precipitation calculations made abroad not only do not encompass the entire process of precipitation formation, but do not even attempt to compute the growth of discrete droplets with allowance for changes in the microstructure of a cloud during the process of cloud development.

At the GGO, in 1961, precipitation calculations were performed for the case of a cloud with ascending currents of variable velocity. This represents the furthest step in the development of the theory of precipitation. These calculations were carried out by I͡u. A. Barukova and T. S. Uchevatkina, using the "Ural" electronic digital computer. Similar, but cruder, calculations were performed at the Alpine Geophysical Institute by G. K. Sulakvelidze and his associates.

The height-dependent variation of the velocity of ascending currents was assumed in our computations to be the same as that obtained by the slice method, based on the data of aerological soundings.

An example of the calculation of the velocity of ascending motions is given in Figure 1. The legend designates the actual values of the maximum rate of cloud development as obtained by G. Z. Eidinova (Geophysical Institute AN GruzSSR) with range-finder observations of cloud growth. The difference between the theoretical and the actual values of the maximum velocity are within the limits of computational error, which in this case is equal to ± 4.5 m/s. An experimental confirmation of this curve (velocity vs height) was obtained by G. K. Sulakvelidze and his associates in 1959 by means of radar observations of the motions in clouds, employing quasi-constant-level balloons with reflectors.

Figure 2 shows the change in the droplet size vs height in a cloud with an ascending current of variable velocity having the same profile as in Figure 1.

The problem of the change in form of the size distribution of droplets during the process of cloud development is still unsolved. In all calculations, it has been assumed that only the distribution parameters (liquid-water content, and the radius of droplets of maximum liquid-water content) vary, while the functional dependence n(r) is preserved.

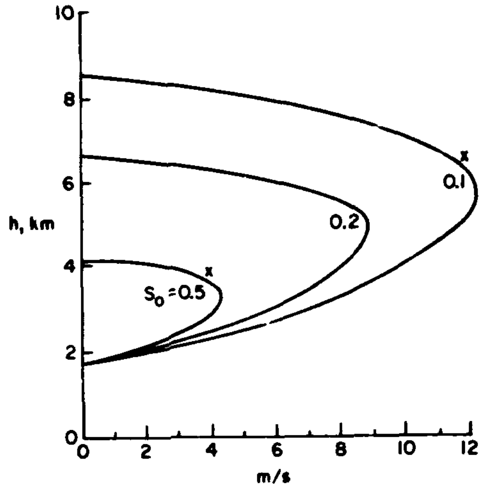

Figure 1. The Rate of Ascending Cu·· ·nts in Clouds vs Height on 6 June 1959, Based on the Data of Calculations. The "x" sign indicates the actual values of the maximum rate based on the data of ı ange-finding observations

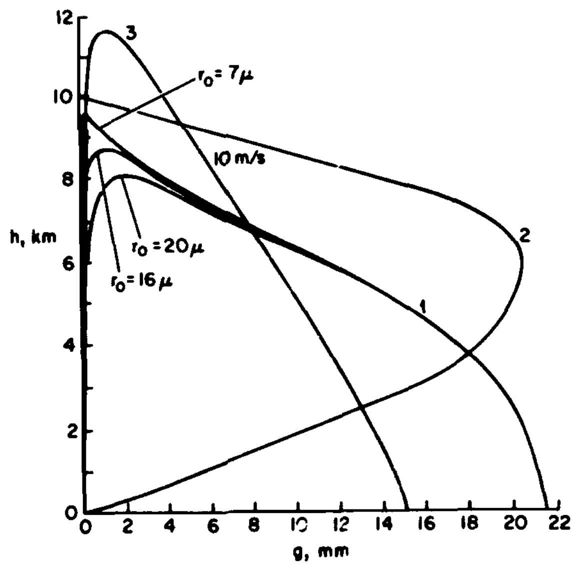

Figure 2. Height-dependent Variation of Particle Sizes in a Cloud With an Ascending Current o' Variable Velocity. Curve 1 shows different values of the initial droplet radius; Curve 2 shows the change in velocity vs height; Curve 3 shows particle growth at a constant velocity equal to the mean valu· of the velocity (10 m/s)

3. CALCULATIONS ON THE GROWTH OF CONVECTIVE CLOUDS

It was indicated in the previous section that the fall of precipitation depends primarily on the conditions of the vertical development of the clouds. It is possible to calculate the rate of cloud growth from the data of aerological soundings by using the slice method, which was created in 1938 by J. Bjerknes and developed by S. Petterssen (1939), A. F. Di͡ubi͡uk (1945), and N. S. Shishkin (1954, 1960). This method accounts for the release of convective energy during the development of a certain number of clouds, and for the energy losses from the compensating descent of the ambient air. The rate of ascent, v, of a cloud mass to level z is determined by the equation.

$$\Delta\left(\frac{v^2}{2}\right) = \frac{T_0 - T_{d_n}}{6T_0} \quad c_p \sum_{k=1}^{n} \left| (T_w - T)k - S(T_w - T_d)_k \right| \quad , \tag{1}$$

where T_0 is the air temperature at the base of the cloud; T_k is the air temperature at the top of the k-th layer, T, T_{wk}, T_{dk} is the temperature of the air rising from the base to the top of the k-th layer for the wet and the dry adiabat, respectively; c_p is the specific heat of the air at constant pressure; and S is the amount of clouds (10/10 cloud cover is taken as a unit). The layers are selected from an aerological diagram, the most useful layers having a thickness of 50-100 mb. Summation is performed over all layers from the cloud base to the cloud top, which is determined by the condition

$$\sum_{k=1}^{n} \left| (T_w - T)_k - S(T_w - T_d)_k \right| = 0 \quad . \tag{2}$$

One can compute the optimum amount of clouds at which the maximum amount of convective energy is released. It is equal to

$$S_{opt} = 1 - \sqrt{\frac{\sum_{k=1}^{n} (T - T_d)_k}{\sum_{k=1}^{n} (T_w - T_d)_k}} \tag{3}$$

and is determined by the condition that is most favorable for the development of thick convective clouds producing thunderstorms, showers, and hail. At the GGO, very simple techniques have been developed for graphically determining the quantities that enter into Eqs. (1), (2), and (3) from an aerological diagram.

As a result of the calculations, it is easy to find the maximum possible height of the tops of convective clouds, the rate of their vertical development, and the change in that rate with height and time.

Figure 3 shows the time-dependent change in the rate of cloud development for the same case, as is shown in Figure 1. Here, the condition of growth are calculated at different development stages as determined by the optimum amount of cloudiness for the corresponding layers. The clouds are assumed to be cylindrical in shape and, therefore, the rate of ascent of a cloud mass at a given instant must be identical for all layers.

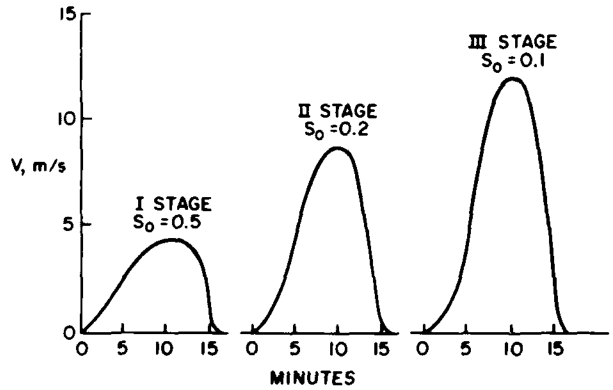

Figure 3. Time-dependent Pulsation Changes in the Velocity of Ascending Currents on 6 June 1959, Based on Computational Data

It is possible to calculate the rate of both cloud growth and cloud dissipation, in an unstable stratification of the atmosphere, due to convection with an active descending current.

The beginning time of each stage is unknown. The solution to this problem requires a detailed experimental study of the diurnal trend of the atmosphere's energy balance at various heights. Such studies have been begun by N. I. Vul'fson and a number of foreign scientists. The sequence time of the different stages of convection development can be roughly determined on the basis of data on both the influx of solar heat to the earth's surface and the transport of heat in the convection process.

Data, which are based on the slice method and the theory of precipitation, have already made it possible, at present, to forecast precipitation from air mass showers and to predict hail conditions.

An alternative forecast for thunderstorms and showers was tried in 1956 and 1957 at 26 Administrations of the Hydrometeorological Service and indicated a mean accuracy for air mass processes of 92 percent. A total of more than 1500 experimental forecasts was issued.

However, the method of calculation was complex, and the use of the method in actual operations was difficult. At present, the calculations have been substantially simplified; and it has been shown possible to predict hail conditions, and the amount of precipitation from air mass showers.

The method of forecasting hail conditions, which was verified by the author along with associates from the ZakNIGMI and the Geophysical Institute of the AN GruzSSR in the summer of 1960 in Alazani Valley, showed a verification of 92 percent after some further improvement. The accuracy of the forecasts was 91 percent for days with actual hail. Of the 21 days with hail in the zone of 100 km radius around Ruispiri, where the radiosondes were taken, a correct forecast was given on 19 days. Here, both air mass and frontal cases of hail were considered.

The author's verification of the method of forecasting the amount of air mass shower precipitation, which was made during the summer of 1960 in the Ukrainian SSR (in a zone with a radius of about 100 km around the Krivoi Rog radiosonde station) showed the following results.

The verification of the alternate forecasts was 90 percent. The mean error in forecasting the daily amount of air mass shower precipitation was about 50 percent. Table 1 presents data on the accuracy of forecasts for 26 days with air mass showers.

Table 1. Forecast Errors

	Maximum amount of precipitation			Average amount of precipitation per area		
	>10 mm	5-10 mm	<5 mm	>0.5 mm	0.1-0.5 mm	<0.1mm
% of cases	8	27	65	4	38	58

The table shows that the largest forecasting errors occurred in a small number of cases.

This technique must be verified with additional data.

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13. ABSTRACT

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